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Presented for filing is a new original patent application of:

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WEN & GREGORY P. BALA
Title: SUBDIVIDING A DIGITAL DENTITION MODEL

Enclosed are the following papers, including all those required to receive a filing date under 37 CFR §1.53(b):

	<u>Pages</u>
Specification	16
Claims	28
Abstract	1
Declaration	[To Be Filed At A Later Date]
Drawing(s)	14

Enclosures:

- Postcard.

This application is entitled to small entity status. A small entity statement will be filed at a later date.

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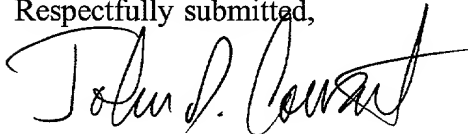
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Respectfully submitted,



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Enclosures

PATENT APPLICATION
SUBDIVIDING A DIGITAL DENTITION MODEL

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SUBDIVIDING A DIGITAL DENTITION MODEL

RELATED APPLICATIONS

This application is a continuation-in-part of U.S. patent application 09/169,276, filed on October 8, 1998, and entitled "Computer Automated Development of an Orthodontic Treatment Plan and Appliance," which claims priority from PCT application PCT/US98/12681, filed on June 19, 1998, and entitled "Method and System for Incrementally Moving Teeth" (attorney docket number 18563-000120), which claims priority from U.S. patent application 08/947,080, filed on October 8, 1997, which claims priority from U.S. provisional application 60/050,342, filed on June 20, 1997, all of which are incorporated by reference into this application.

TECHNOLOGICAL FIELD

The invention relates generally to the fields of dentistry and orthodontics and, more particularly, to subdividing a digital model of a patient's dentition.

BACKGROUND

Two-dimensional (2D) and three-dimensional (3D) digital image technology has recently been tapped as a tool to assist in dental and orthodontic treatment. Many treatment providers use some form of digital image technology to study the dentitions of patients. U.S. patent application 09/169,276, incorporated by reference above, describes the use of 2D and 3D image data in forming a digital model of a patient's dentition, including models of individual dentition components. Such models are useful, among other things, in developing an orthodontic treatment plan for the patient, as well as in creating one or more orthodontic appliances to implement the treatment plan.

SUMMARY

The inventors have developed several computer automated techniques for subdividing, or segmenting, a digital dentition model into models of individual dentition components. These dentition components include, but are not limited to, tooth crowns, tooth roots, and gingival regions. The segmentation techniques include both human assisted and fully automated techniques. Some of the human assisted techniques allow a human user to provide “algorithmic hints” by identifying certain features in the digital dentition model. The identified features then serve as a basis for automated segmentation. Some techniques act on a volumetric 3D image model, or “voxel representation,” of the dentition, and other techniques act on a geometric 3D model, or “geometric representation.”

In one aspect, a computer implementing the invention receives a data set that forms a three-dimensional (3D) representation of the patient’s dentition, applies a test to the data set to identify data elements that represent portions of the individual component, and creates a digital model of the individual component based upon the identified data elements. Some implementations require the computer to identify data elements that form one or more 2D cross-sections of the dentition in one or more 2D planes intersecting the dentition. In many of these embodiments, these 2D planes are roughly parallel to the dentition’s occlusal plane. The computer analyzes the features of the 2D cross-sections to identify data elements that correspond to the individual component to be modeled. For example, one technique requires the computer to identify cusps in the 2D cross-sectional surface of the dentition, where the cusps represent the locations of an interproximal margin between teeth in the dentition. One variation of this technique allows the computer to confine its search for cusps in one 2D plane to areas in the vicinity of cusps already identified on another 2D plane. Another variation allows the computer to link cusps on adjacent 2D planes to form a solid surface representing the interproximal margin. Some embodiments allow the computer to receive input from a human user identifying the cusp locations in one or more of the 2D cross sections.

Other embodiments require the computer to identify data elements that represent a structural core, or skeleton, of each individual component to be modeled. The computer creates the model by linking other data elements representing the individual component to the structural

core.

In another aspect, a computer implementing the invention receives a three-dimensional (3D) data set representing the patient's dentition, applies a test to identify data elements that represent an interproximal margin between two teeth in the dentition, and applies another
5 computer-implemented test to select data elements that lie on one side of the interproximal margin for inclusion in the digital model. Some implementations require the computer to identify data elements that form one or more 2D cross-sections of the dentition in one or more 2D planes intersecting the dentition roughly parallel to the dentition's occlusal plane.

In another aspect, a computer implementing the invention receives a 3D data set
10 representing at least a portion of the patient's dentition, including at least a portion of a tooth and gum tissue surrounding the tooth; applies a test to identify data elements lying on a gingival boundary that occurs where the tooth and the gum tissue meet; and applies a test to the data elements lying on the boundary to identify other data elements representing portions of the tooth.

Other embodiments and advantages are apparent from the detailed description and the
15 claims below.

DESCRIPTION OF THE DRAWINGS

FIGS. 1A, 1B, and 2 are partial views of a dentition model as displayed on a computer monitor and segmented with a human operated saw tool.

20 FIG. 3 is a partial view of a dentition model as displayed on a computer monitor and segmented with a human operated eraser tool.

FIG. 4 is a view of a dentition model for which a feature skeleton has been identified.

FIGS. 5 and 6 are flow diagram for a feature skeleton analysis technique used in segmenting a dentition model.

25 FIG. 7A is a horizontal 2D cross-sectional view of a dentition model.

FIG. 7B is a side view of a dentition model intersected by several 2D planes.

FIG. 8 is a flow diagram for a 2D slice analysis technique used in segmenting a dentition model.

FIGS. 9 and 10A through 10C each shows a group of voxels in a 2D slice of a dentition

model.

FIG. 11 is a flow chart for an automatic cusp detection technique used in segmenting a dentition model.

FIG. 12 is a horizontal 2D cross-section of a dentition model illustrating a neighborhood
5 filtered automatic cusp detection technique used in segmenting the dentition model.

FIG. 13 is shows two groups of voxels in a 2D slice of a dentition model illustrating the neighborhood filtered automatic cusp detection technique.

FIG. 14 is a flow chart for the neighborhood filtered automatic cusp detection technique.

FIG. 15 is a horizontal 2D cross-section of a dentition model illustrating an arch curve
10 fitting technique used in segmenting the dentition model.

FIG. 16 is a flow chart for the arch curve fitting technique.

FIG. 17 is a horizontal 2D cross-section of a dentition model illustrating a curve creation
technique for use with the arch curve fitting technique.

FIG. 18 is a flow diagram for the curve creation technique.

FIGS. 19A and 19B are a perspective view and a vertical 2D cross-sectional view of a
15 dentition model illustrating another technique for use in segmenting the dentition model.

FIGS. 20 and 21 are flow diagrams of this technique.

FIG. 22 is a vertical 2D cross-sectional view of a dentition model illustrating a gingival
margin detection technique for use in segmenting the dentition model.

FIG. 23 shows a group of voxels in a 2D slice of a dentition model illustrating a gingival
20 margin detection technique.

FIG. 24 is a flow diagram for the gingival margin detection technique.

DETAILED DESCRIPTION

25 U.S. patent application 09/169,276 describes techniques for generating a 3D digital model of a patient's dentition, including the crowns and roots of the patients teeth as well as the surrounding gum tissue. One such technique involves creating a physical model of the dentition from a material such as plaster and then digitally imaging the model with a laser scanner or a destructive scanning system. The described techniques are used to produce a volumetric 3D

image model (“volume element representation” or “voxel representation”) and a geometric 3D surface model (“geometric model”) of the dentition. The techniques described below act on one or both of these types of 3D dentition models. In creating a voxel representation, the physical model is usually embedded in a potting material that contrasts sharply with the color of the model to enhance detection of the dentition features. A white dentition model embedded in a black potting material provides the sharpest contrast. A wide variety of information is used to enhance the 3D model, including data taken from photographic images, 2D and 3D x-rays scans, computed tomography (CT) scans, and magnetic resonance imaging (MRI) scans of the patient's dentition.

Some computer-implemented techniques for segmenting a 3D dentition model into models of individual dentition components require a substantial amount of human interaction with the computer. One such technique, which is shown in FIGS. 1A, 1B, and 2, provides a graphical user interface with a feature that imitates a conventional saw, allowing the user to identify components to be cut away from the dentition model 100. The graphical user interface provides a rendered 3D image 100 of the dentition model, either at one or more static views from predetermined positions, as shown in FIGS. 1A and 1B, or in a “full 3D” mode that allows the user to alter the viewing angle, as shown in FIG. 2. The saw tool is implemented as a set of mathematical control points 102, represented graphically on the rendered image 100, which define a 3D cutting surface 104 that intersects the volumetric or geometric dentition model. The computer subdivides the data elements in the dentition model by performing a surface intersection operation between the 3D cutting surface 104 and the dentition model. The user sets the locations of the mathematical control points, and thus the geometry and position of the 3D cutting surface, by manipulating the control points in the graphical display with an input device, such as a mouse. The computer provides a visual representation 104 of the cutting surface on the display to assist the user in fitting the surface around the individual component to be separated. Once the intersection operation is complete, the computer creates a model of the individual component using the newly segmented data elements.

Another technique requiring substantial human interaction, shown in FIG. 3, is a graphical user interface with a tool that imitates a conventional eraser. The eraser tool allows the user to

isolate an individual dentition component by removing portions of the dentition model that surround the individual component. The eraser tool is implemented as a 3D solid 110, typically having the shape of a rectangular prism, or a curved surface that matches the shape of a side surface of a tooth. The solid is made as small as possible, usually only a single voxel thick, to minimize degradation of the data set. As with the saw technique above, the graphical user interface presents the user with a rendered 3D image 112 of the dentition model at one or more predetermined static views or in a full 3D mode. The user identifies portions of the dentition model for removal by manipulating a graphical representation 110 of the 3D solid with an input device. In alternative embodiments, the computer either removes the identified portions of the dentition model as the user moves the eraser 112, or the computer waits until the user stops moving the eraser and provides an instruction to remove the identified portions. The computer updates the display in real time to show the path 114 of the eraser through the dentition model.

Other computer-implemented segmentation techniques require little or no human interaction during the segmentation process. One such technique, which is illustrated in FIG. 4, involves the application of conventional “feature skeleton” analysis to a volumetric representation of the dentition model. This technique is particularly useful in identifying and modeling individual teeth. In general, a computer applying this technique identifies a core of voxels, that forms a skeleton 122 for the dentition 120. The skeleton 122 roughly resembles the network of biological nerves within patient’s teeth. The computer then divides the skeleton 122 into branches 124, each containing voxels that lie entirely within one tooth. One technique for identifying the branches is by defining a plane 126 that cuts through the skeleton 122 roughly parallel to the occlusal plane of the patient’s dentition (“horizontal plane”). Each branch 124 intersects the horizontal plane 126 at one or more points, or clusters, that are relatively distant from the clusters associated with the other branches. The computer forms the individual tooth models by linking other voxels to the appropriate branches 124 of the skeleton.

FIG. 5 describes a particular technique for forming a skeleton in the dentition model. The computer first identifies the voxels in the dentition model that represent the tooth surfaces (step 130). For a voxel representation that is created from a physical model embedded in a sharply contrasting material, identifying the tooth surfaces is as simple as identifying the voxels at which

sharp changes in image value occur, as described in U.S. patent application 09/169,276. The computer then calculates, for each voxel in the model, a distance measure indicating the physical distance between the voxel and the nearest tooth surface (step 132). The computer identifies the voxels with the largest distance measures and labels each of these voxels as forming a portion of the skeleton (step 134). Feature skeleton analysis techniques are described in more detail in the following publications: (1) Gagvani and Silver, "Parameter Controlled Skeletons for 3D Visualization," Proceedings of the IEEE Visualization Conference (1997); (2) Bertrand, "A Parallel Thinning Algorithm for Medial Surfaces," Pattern Recognition Letters, v. 16, pp. 979-986 (1995); (3) Mukherjee, Chatterji, and Das, "Thinning of 3-D Images Using the Safe Point Thinning Algorithm (SPTA)," Pattern Recognition Letters, v. 10, pp. 167-173 (1989); (4) Niblack, Gibbons, and Capson, "Generating Skeletons and Centerlines from the Distance Transform," CVGIP: Graphical Models and Image Processing, v. 54, n. 5, pp. 420-437 (1992).

Once a skeleton has been identified, the computer uses the skeleton to divide the dentition model into 3D models of the individual teeth. FIG. 6 shows one technique for doing so. The computer first identifies those portions of the skeleton that are associated with each individual tooth. To do so, the computer defines a plane that is roughly parallel to the dentition's occlusal surface and that intersects the skeleton near its base (step 136). The computer then identifies points at which the plane and the skeleton intersect by identifying each voxel that lies on both the skeleton and the plane (step 138). In general, a single tooth includes all of the voxels that lie in a particular branch of the skeleton; and because the plane intersects the skeleton near its base, voxels that lie together in a branch of the skeleton usually cluster together on the intersecting plane. The computer is able to locate the branches by identifying voxels on the skeleton that lie within a particular distance of each other on the intersecting plane (step 140). The computer then identifies and labels all voxels on the skeleton that belong to each branch (step 142).

Once the branches are identified, the computer links other voxels in the model to the branches. The computer begins by identifying a reference voxel in each branch of the skeleton (step 144). For each reference voxel, the computer selects an adjacent voxel that does not lie on the skeleton (step 146). The computer then processes the selected voxel, determining whether the voxel lies outside of the dentition, *i.e.*, whether the associated image value is above or below

a particular threshold value (step 148); determining whether the voxel already is labeled as belonging to another tooth (step 150); and determining whether the voxel's distance measure is greater than the distance measure of the reference voxel (step 152). If none of these conditions is true, the computer labels the selected voxel as belonging to the same tooth as the reference voxel (step 154). The computer then repeats this test for all other voxels adjacent to the reference voxel (step 156). Upon testing all adjacent voxels, the computer selects one of the adjacent voxels as a new reference point, provided that the adjacent voxel is labeled as belonging to the same tooth, and then repeats the test above for each untested voxel that is adjacent to the new reference point. This process continues until all voxels in the dentition have been tested.

FIGS. 7A and 7B illustrate another technique for identifying and segmenting individual teeth in the dentition model. This technique, called "2D slice analysis," involves dividing the voxel representation of the dentition model into a series of parallel 2D planes 160, or slices, that are each one voxel thick and that are roughly parallel to the dentition's occlusal plane. Each of the 2D slices 160 includes a 2D cross-section 162 of the dentition, the surface 164 of which represents the lingual and buccal surfaces of the patient's teeth and/or gums. The computer inspects the cross-section 162 in each 2D slice 160 to identify voxels that approximate the locations of the interproximal margins 166 between the teeth. These voxels lie at the tips of cusps 165 in the 2D cross-sectional surface 164. The computer then uses the identified voxels to create 3D surfaces 168 intersecting the dentition model at these locations. The computer segments the dentition model along these intersecting surfaces 168 to create individual tooth models.

FIG. 8 describes a particular implementation of the 2D slice analysis technique. The computer begins by identifying the voxels that form each of the 2D slices (step 170). The computer then identifies, for each 2D slice, the voxels that represent the buccal and lingual surfaces of the patient's teeth and gums (step 172) and defines a curve that includes all of these voxels (step 174). This curve represents the surface 164 of the 2D cross-section 162.

The computer then calculates the rate of curvature (*i.e.*, the derivative of the radius of curvature) at each voxel on the 2D cross-sectional surface 164 (step 176) and identifies all of the voxels at which local maxima in the rate of curvature occur (step 178). Each voxel at which a

local maximum occurs represents a “cusp” in the 2D cross-sectional surface 164 and roughly coincides with an interproximal margin between teeth. In each 2D slice, the computer identifies pairs of these cusp voxels that correspond to the same interproximal margin (step 180), and the computer labels each pair to identify the interproximal margin with which it is associated (step 182). The computer then identifies the voxel pairs on all of the 2D slices that represent the same interproximal margins (step 184). For each interproximal margin, the computer fits a 3D surface 168 approximating the geometry of the interproximal margin among the associated voxel pairs (step 186).

FIG. 9 illustrates one technique for creating the 3D surfaces that approximate the interproximal margins. For each pair of cusp voxels 190a-b in a 2D slice that are associated with a particular interproximal region, the computer creates a line segment 192 bounded by these cusp voxels 190a-b. The computer changes the colors of the voxels in the line segment, including the cusp voxels 190a-b that bound the segment, to contrast with the other voxels in the 2D slice. The computer creates line segments in this manner in each successive 2D slice, forming 3D surfaces that represent the interproximal regions. All of the voxels that lie between adjacent ones of these 3D surfaces represent an individual tooth.

FIGS. 10A through 10C illustrate a refinement of the technique shown in FIG. 9. The refined technique involves the projection of a line segment 200 from one slice onto a line segment 206 on the next successive slice to form, for the associated interproximal margin, a 2D area bounded by the cusp voxels 202a-b, 204a-b of the line segments 200, 206. If the line segments 200, 206 are oriented such that any voxel on one segment 200 is not adjacent to a voxel on the other segment 206, as shown in FIG. 10A, then the resulting 3D surface is discontinuous, leaving unwanted “islands” of white voxels 208, 210.

The computer eliminates these discontinuities by creating two new line segments 212, 214, each of which is bounded by one cusp voxel 202a-b, 204a-b from each original line segment 200, 206, as shown in FIG. 10B. The computer then eliminates the islands between the new line segments 212, 214 by changing the colors of all voxels between the new line segments 212, 214, as shown in FIG. 10C.

Automated segmentation is enhanced through a technique known as “seed cusp detection.”

The term “seed cusp” refers to a location at which an interproximal margin meets the patient’s gum tissue. In a volumetric representation of the patient’s dentition, a seed cusp for a particular interproximal margin is found at the cusp voxel that lies closest to the gumline. By applying the seed cusp detection technique of the 2D slice analysis, the computer is able to identify all of the seed cusp voxels in the 3D model automatically.

FIG. 11 shows a particular implementation of the seed cusp detection technique, in which the computer detects the seed cusps by identifying each 2D slice in which the rate of curvature of a cusp first falls below a predetermined threshold value. The computer begins by selecting a 2D slice that intersects all of the teeth in the arch (step 220). The computer attempts to select a slice that is near the gingival regions but that does not include any voxels representing gingival tissue. The computer then identifies all of the cusp voxels in the 2D slice (step 222). If the rate of curvature of the 2D cross-section at any of the cusp voxels is less than a predetermined threshold value, the computer labels that voxel as a seed cusp (step 224). The computer then selects the next 2D slice, which is one voxel layer closer to the gingival region (step 226), and identifies all of the cusp voxels that are not associated with a cusp for which the computer has already identified a seed cusp (step 228). If the rate of curvature of the 2D cross-section is less than the predetermined threshold value at any of these cusp voxels, the computer labels the voxel as a seed cusp (step 230) and proceeds to the next 2D slice. The computer continues in this manner until a seed cusp voxel has been identified for each cusp associated with an interproximal margin (step 232).

FIGS. 12, 13, and 14 illustrate a technique, known as “neighborhood-filtered cusp detection,” by which the computer focuses its search for cusps on one 2D slice to neighborhoods 244, 246 of voxels defined by a pair of previously detected cusp voxels 240, 242 on another 2D slice. Upon detecting a pair of cusp voxels 240, 242 in a 2D slice at level N (step 250), the computer defines one or more neighborhoods 244, 246 that include a predetermined number of voxels surrounding the pair (step 252). The computer then projects the neighborhoods onto the next 2D slice at level N+1 by identifying the voxels on the next slice that are immediately adjacent the voxels in the neighborhoods on the original slice (step 254). The neighborhoods are made large enough to ensure that they include the cusp voxels on the N+1 slice. In the example

of FIG. 13, each cusp voxel 240, 242 lies at the center of a neighborhood 244, 246 of twenty-five voxels arranged in a 5 x 5 square.

In searching for the cusp voxels on the N+1 slice, the computer tests the image values for all voxels in the projected neighborhoods to identify those associated with the background image and those associated with the dentition (step 256). In the illustrated example, voxels in the background are black and voxels in the dentition are white. The computer identifies the cusp voxels on the N+1 slice by locating the pair of black voxels in the two neighborhoods that lie closest together (step 258). The computer then repeats this process for all remaining slices (step 259).

FIGS. 15 and 16 illustrate another technique, known as “arch curve fitting,” for identifying interproximal margins between teeth in the dentition. The arch curve fitting technique, which also applies to 2D cross-sectional slices of the dentition, involves the creation of a curve 260 that fits among the voxels on the 2D cross-sectional surface 262 of the dentition arch 264. A series of closely-spaced line segments 268, each bounded by the cross-sectional surface 268, are formed along the curve 260, roughly perpendicular to the curve 260, throughout the 2D cross-section 264. In general, the shortest of these line segments 268 lie on or near the interproximal margins; thus computer identifies the cusps that define the interproximal margins by determining the relative lengths of the line segments 268.

When applying the arch curve fitting technique, the computer begins by selecting a 2D slice (step 270) and identifying the voxels associated with the surface 262 of the cross-sectional arch 264 (step 272). The computer then defines a curve 260 that fits among the voxels on the surface 262 of the arch (step 274). The computer creates the curve using any of a variety of techniques, a few of which are discussed below. The computer then creates a series of line segments that are roughly perpendicular to the curve and are bounded by the cross-sectional surface 262 (step 276). The line segments are approximately evenly spaced with a spacing distance that depends upon the required resolution and the acceptable computing time. Greater resolution leads to more line segments and thus greater computing time. In general, a spacing on the order of 0.4 mm is sufficient in the initial pass of the arch curve fitting technique.

The computer calculates the length of each line segment (step 278) and then identifies those

line segments that form local minima in length (step 280). These line segments roughly approximate the locations of the interproximal boundaries, and the computer labels the voxels that bound these segments as cusp voxels (step 282). The computer repeats this process for each of the 2D slices (step 284) and then uses the cusp voxels to define 3D cutting surfaces that
5 approximate the interproximal margins.

In some implementations, the computer refines the arch cusp determination by creating several additional sets of line segments, each centered around the arch cusps identified on the first pass. The line segments are spaced more narrowly on this pass to provide greater resolution in identifying the actual positions of the arch cusps.

10 The computer uses any of a variety of curve fitting techniques to create the curve through the arch. One technique involves the creation of a catenary curve with endpoints lying at the two ends 265, 267 (FIG. 15) of the arch. The catenary curve is defined by the equation $y = a + b \cdot \cosh(cx)$, and the computer fits the curve to the arch by selecting appropriate values for the constants **a**, **b**, and **c**. Another technique involves the creation of two curves, one fitted
15 among voxels lying on the front surface 271 of the arch, and the other fitted among voxels on the rear surface 273. A third curve, which guides the placement of the line segments above, passes through the middle of the area lying between the first two curves.

FIGS. 17 and 18 illustrate another technique for constructing a curve through the arch. This technique involves the creation of a series of initial line segments through the arch 264 and
20 the subsequent formation of a curve 290 fitted among the midpoints of these line segments. This curve 290 serves as the arch curve in the arch curve fitting technique described above.

In applying this technique, the computer first locates an end 265 of the arch (step 300) and creates a line segment 291 that passes through the arch 264 near this end 265 (step 301). The line segment 291 is bounded by voxels 292a-b lying on the surface of the arch. The computer
25 then determines the midpoint 293 of the line segment 291 (step 302), selects a voxel 294 located particular distance from the midpoint 293 (step 304), and creates a second line segment 295 that is parallel to the initial line segment 291 and that includes the selected voxel 294 (step 306). The computer then calculates the midpoint 296 of the second segment 295 (step 308) and rotates the second segment 295 to the orientation 295' that gives the segment its minimum possible length

(step 309). In some cases, the computer limits the second segment 295 to a predetermined amount of rotation (*e.g.*, $\pm 10^\circ$).

The computer then selects a voxel 297 located a particular distance from the midpoint 296 of the second segment 295 (step 310) and creates a third line segment 298 that is parallel to the second line segment 295 and that includes the selected voxel 297 (step 312). The computer calculates the midpoint 299 of the third segment 298 (step 314) and rotates the segment 298 to the orientation 298' that gives the segment its shortest possible length (step 316). The computer continues adding line segments in this manner until the other end of the cross-sectional arch is reached (step 318). The computer then creates a curve that fits among the midpoints of the line segments (step 320) and uses this curve in applying the arch fitting technique described above.

FIGS. 19A, 19B and 20 illustrate an alternative technique for creating 3D surfaces that approximate the geometries and locations of the interproximal margins in the patient's dentition. This technique involves the creation of 2D planes that intersect the 3D dentition model at locations that approximate the interproximal margins. In general, the computer defines a series of planes, beginning with an initial plane 330 at one end 331 of the arch 332, that are roughly perpendicular to the occlusal plane of the dentition model ("vertical" planes). Each plane intersects the dentition model to form a 2D cross-section 334. If the planes are spaced sufficiently close to each other, the planes with the smallest cross-sectional areas approximate the locations of the interproximal margins in the dentition. The computer locates the interproximal regions more precisely by rotating each plane about two orthogonal axes 336, 338 until the plane reaches the orientation that yields the smallest possible cross-sectional area.

In one implementation of this technique, the computer first identifies one end of the arch in the dentition model (step 340). The computer then creates a vertical plane 330 through the arch near this end (step 342) and identifies the centerpoint 331 of the plane 330 (step 344). The computer then selects a voxel located a predetermined distance from the centerpoint (step 345) and creates a second plane 333 that is parallel to the initial plane and that includes the selected voxel (step 346). The computer calculates the midpoint of the second plane (step 348) and rotates the second plane about two orthogonal axes that intersect at the midpoint (step 350). The computer stops rotating the plane upon finding the orientation that yields the minimum cross-

sectional area. In some cases, the computer limits the plane to a predetermined amount of rotation (*e.g.*, $\pm 10^\circ$ about each axis). The computer then selects a voxel located a particular distance from the midpoint of the second plane (step 352) and creates a third plane that is parallel to the second plane and that includes the selected voxel (step 354). The computer calculates the midpoint of the third plane (step 356) and rotates the plane to the orientation that yields the smallest possible cross-sectional area (step 357). The computer continues adding and rotating planes in this manner until the other end of the arch is reached (step 358). The computer identifies the planes at which local minima in cross-sectional area occur and labels these planes as “interproximal planes,” which approximate the locations of the interproximal margins (step 360).

One variation of this technique, described in FIG. 21, allows the computer to refine its identification of interproximal planes by creating additional, more closely positioned planes in areas around the planes labeled as interproximal. The computer first creates a curve that fits among the midpoints of the planes labeled as interproximal planes (step 372) and then creates a set of additional planes along this curve (step 374). The additional planes are not evenly spaced along the curve, but rather are concentrated around the interproximal margins. The planes in each interproximal area are spaced very closely (*e.g.*, 0.05 mm from each other). The computer rotates each of the newly constructed planes about two orthogonal axes until the plane reaches its minimum cross-sectional area (step 376). The computer then selects the plane in each cluster with the smallest cross-sectional area as the plane that most closely approximates the interproximal margin (step 378).

FIGS. 22, 23, and 24 illustrate a technique for identifying the gingival margin that defines the boundary between tooth and gum in the patient’s dentition. This technique involves the creation of a series of horizontal 2D planes 380, or slices, that intersect the dentition model roughly perpendicular to the occlusal plane (see FIG. 19A). The cross-sectional surface 382 of the dentition model in each of these planes 380 includes cusps 384, 386 that represent the gingival margin. The computer identifies the gingival margin by applying one or more of the cusp detection techniques described above.

One technique is very similar to the neighborhood filtered cusp detection technique

described above, in that voxel neighborhoods 388, 390 are defined on one of the 2D planes to focus the computer's search for cusps on an adjacent 2D plane. Upon detecting a pair of cusps 384, 386 on one 2D plane (step 400), the computer defines one or more neighborhoods 388, 390 to include a predetermined number of voxels surrounding the pair (step 402). The computer
5 projects the neighborhoods onto an adjacent 2D plane by identifying the voxels on the adjacent plane that correspond to the voxels in the neighborhoods 388, 390 on the original plane (step 404). The computer then identifies the pair of black voxels that lie closest together in the two neighborhoods on the adjacent plane, labeling these voxels as lying in the cusp (step 406). The computer repeats this process for all remaining planes (step 408).

10 Many of these automated segmentation techniques are even more useful and efficient when used in conjunction with human-assisted techniques. For example, techniques that rely on the identification of the interproximal or gingival margins function more quickly and effectively when a human user first highlights the interproximal or gingival cusps in a graphical representation of the dentition model. One technique for receiving this type of information from
15 the user is by displaying a 2D or 3D representation and allowing the user to highlight individual voxels in the display. Another technique allows the user to scroll through a series of 2D cross-sectional slices, identifying those voxels that represent key features such as interproximal or gingival cusps. Some of these techniques rely on user interface tools such as cursors and bounding-box markers.

20 In many instances, the computer creates proposals for segmenting the dentition model and then allows the user to select the best alternative. For example, one version of the arch curve fitting technique requires the computer to create a candidate catenary or spline curve, which the user is allowed to modify by manipulating the mathematical control parameters. Other techniques involve displaying several surfaces that are candidate cutting surfaces and allowing
25 the user to select the appropriate surfaces.

Some implementations of the invention are realized in digital electronic circuitry, such as an application specific integrated circuit (ASIC); others are realized in computer hardware, firmware, and software, or in combinations of digital circuitry and computer components. The invention is usually embodied, at least in part, as a computer program tangibly stored in a

machine-readable storage device for execution by a computer processor. In these situations, methods embodying the invention are performed when the processor executes instructions organized into program modules, operating on input data and generating output. Suitable processors include general and special purpose microprocessors, which generally receive

5 instructions and data from read-only memory and/or random access memory devices. Storage devices that are suitable for tangibly embodying computer program instructions include all forms of non-volatile memory, including semiconductor memory devices, such as EPROM, EEPROM, and flash memory devices; magnetic disks such as internal hard disks and removable disks; magneto-optical disks; and CD-ROM.

10 The invention has been described in terms of particular embodiments. Other embodiments are within the scope of the following claims.

CLAIMS

1. A computer-implemented method for use in creating a digital model of an individual component of a patient's dentition, the method comprising:
 - (a) receiving a data set that forms a three-dimensional (3D) representation of the patient's dentition;
 - (b) applying a computer-implemented test to the data set to identify data elements that represent portions of an individual component of the patient's dentition; and
 - (c) creating a digital model of the individual component based upon the identified data elements.
2. The method of claim 1, wherein the data set includes data taken from at least one of the following sources: two-dimensional (2D) x-ray data and three-dimensional (3D) x-ray data.
3. The method of claim 1, wherein the data set includes data taken from at least one of the following sources: computed tomography (CT) scan data and magnetic resonance imaging (MRI) scan data.
4. The method of claim 1, wherein the data set includes data taken from a photographic image of the patient's dentition.
5. The method of claim 1, wherein some of the data is obtained by imaging a physical model of the patient's teeth.
6. The method of claim 1, wherein some of the data is obtained by imaging the patient's teeth directly.
7. The method of claim 1, wherein the data set forms a 3D volumetric representation of the

patient's dentition.

8. The method of claim 1, wherein the data set includes geometric surface data that forms a 3D geometric surface model of the patient's dentition.

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9. The method of claim 1, wherein the individual component is an individual tooth in the patient's dentition.

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10. The method of claim 1, wherein the individual component includes gum tissue found in the patient's dentition.

11. The method of claim 1, wherein applying the computer-implemented test includes receiving information input by a human user to identify a boundary of the individual component to be modeled.

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12. The method of claim 11, wherein receiving information includes receiving position data from a computer-implemented tool through which the human user identifies the boundary in a graphical representation of the patient's dentition.

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13. The method of claim 12, wherein the computer-implemented tool is a saw tool that allows the user to identify the boundary by defining a curve in the graphical representation that separates the data elements associated with the individual component from other elements of the data set.

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14. The method of claim 12, wherein the computer-implemented tool is an eraser tool that allows the user to identify the boundary by erasing a portion of the graphical representation representing the boundary.

15. The method of claim 1, wherein receiving the data, applying the computer-implemented test, and creating the electronic model all are carried out by a computer without human intervention.

5 16. The method of claim 1, wherein applying the computer-implemented test includes automatically applying a rule to identify a boundary of the individual component to be modeled.

17. The method of claim 16, wherein the boundary includes a surface of a tooth.

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18. The method of claim 16, wherein the boundary includes a gingival margin.

19. The method of claim 1, wherein applying the computer-implemented test includes identifying elements of the data set that represent a structural core of the individual component to be modeled and labeling those data elements as belonging to the individual component.

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20. The method of claim 19, wherein the individual component to be modeled includes an individual tooth and the structural core approximately coincides with neurological roots of the tooth.

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21. The method of claim 19, wherein applying the computer-implemented test includes applying a test to link other data elements to those representing the structural core and labeling the linked data elements as belonging to the individual component.

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22. The method of claim 21, wherein applying the test to link other data elements to those representing the structural core includes assigning a distance measure to each element of the data set, where the distance measure indicates a measured distance between a reference point in the dentition and the portion of the dentition represented by the data element to

which the distance measure is assigned.

23. The method of claim 22, wherein applying the test to link other data elements includes linking a data element to the structural core if the assigned distance measure is less than the distance measure assigned to a data element representing a portion of the structural core.

24. The method of claim 22, wherein the reference point lies on a tooth surface.

25. The method of claim 21, wherein applying the test to link other data elements to the structural core includes applying a test to determine whether a data element lies outside of the dentition and, if so, labeling the data element as a background element.

26. The method of claim 25, wherein applying the test to determine whether the data element lies outside of the dentition includes comparing an image value associated with the data element to a threshold value.

27. The method of claim 19, further comprising applying another computer-implemented test to identify elements of the data set that represent a structural core of another individual component of the dentition and labeling those data elements as belonging to the other individual component.

28. The method of claim 27, wherein applying the computer-implemented tests includes applying tests to link other elements of the data set to those representing the structural cores of the individual components and labeling the linked elements as belonging to the individual components to which they are linked.

29. The method of claim 28, wherein applying the tests to link other data elements to the structural cores of the individual components includes determining whether a data element already is labeled as belonging to one of the individual components.

30. The method of claim 1, wherein applying the computer implemented test includes identifying an initial 2D cross-section of the individual component having continuous latitudinal width, a relative minimum value of which occurs at an end of the initial cross-section.

31. The method of claim 30, wherein applying the computer-implemented test includes isolating portions of the data corresponding to the initial 2D cross-section of the individual component to be modeled.

32. The method of claim 31, wherein the received data includes 3D image data obtained by imaging the individual component volumetrically, and wherein isolating portions of the data corresponding to the initial 2D cross-section includes isolating elements of the 3D image data representing the initial 2D cross-section.

33. The method of claim 30, wherein applying the computer-implemented test includes applying a test to identify the end of the initial cross-section at which the relative minimum value of the latitudinal width occurs.

34. The method of claim 33, wherein applying the test to identify the end of the initial cross-section includes:

- (a) establishing line segments within the initial cross-section, each of which is bounded at each end by an endpoint lying on a surface of the individual component, and each of which is roughly perpendicular to a latitudinal axis of the individual component;
- (b) calculating a length for each line segment; and
- (c) identifying elements of the data set that correspond to the endpoints of the line segment with the shortest length.

35. The method of claim 34, wherein applying the computer-implemented test also includes:

- (a) isolating portions of the data set corresponding to other 2D cross-sections of the individual component, all lying in planes parallel to the initial 2D cross-section;
- (b) for each of the other cross-sections, identifying data elements that correspond to endpoints of a line segment representing an end of the cross-section; and
- (c) defining a solid surface that contains all of the identified data elements.

36. The method of claim 35, further comprising labeling the solid surface as representing a surface of the individual component to be modeled.

37. The method of claim 35, further comprising using the data elements identified in the initial cross-section as guides for identifying the data elements in the other cross-sections.

38. The method of claim 34, wherein applying the test to identify the end of the initial cross-section includes first creating an initial curve that is roughly perpendicular to the latitudinal axis of the individual component and that is fitted between the surfaces of the 2D cross-section on which the endpoints of the line segments will lie.

39. The method of claim 38, wherein establishing the line segments includes first establishing a set of initial line segments that are roughly perpendicular to the curve and to the latitudinal axis and that have endpoints lying on the surfaces of the individual component.

40. The method of claim 39, wherein establishing the line segments also includes pivoting each initial line segment about a point at which the initial line segment intersects the curve until the initial line segment has its shortest possible length.

41. The method of claim 40, wherein establishing the line segments also includes:

- (a) locating a midpoint for each of the initial line segments after pivoting; and
- (b) creating a refined curve that passes through all of the midpoints.

42. The method of claim 41, wherein establishing the line segments also includes creating the line segments to be perpendicular to the refined curve.

43. The method of claim 38, wherein the individual component is a tooth and the curve is a portion of a larger curve fitted among the lingual and buccal surfaces of all teeth in a 2D cross-section of a tooth arch in which the tooth lies.

44. The method of claim 43, wherein the larger curve is a catenary.

45. The method of claim 43, wherein the larger curve is created by manipulating mathematical control points to fit the curve to the shape of the cross-section of the tooth arch.

46. The method of claim 34, wherein establishing the line segments includes first establishing an initial line segment by creating a line that intersects the initial 2D cross-section, such that the initial line segment has endpoints that lie on surfaces of the individual component.

47. The method of claim 46, wherein establishing the line segments also includes establishing at least one additional line segment parallel to and spaced a predetermined distance from a previously established line segment.

48. The method of claim 47, wherein establishing the line segments also includes, for each additional line segment, locating a midpoint of the additional line segment and pivoting the additional line segment about the midpoint until the additional line segment has its shortest possible length.

49. The method of claim 48, wherein establishing the line segments also includes limiting the rotation of each additional line segment to no more than a predetermined amount.

50. The method of claim 49, wherein the rotation of each additional line segment is limited to

no more than approximately +/- 10°.

51. The method of claim 48, wherein establishing the line segments also includes establishing a curve that is fitted among the midpoints of the additional line segments.

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52. The method of claim 51, wherein establishing the line segments includes establishing the line segments to be perpendicular to the curve.

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53. The method of claim 52, wherein establishing the line segments includes locating midpoints for each of the line segments and pivoting each line segment about its midpoint until the line segment has its shortest possible length.

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54. The method of claim 30, wherein the individual component is a tooth and the relative minimum value of the initial 2D cross-section lies on an interproximal surface of the tooth.

55. The method of claim 54, wherein identifying the initial 2D cross-section includes isolating elements of the data set that correspond to 2D cross-sections of the tooth lying in parallel planes between the roots and the occlusal surface of the tooth.

56. The method of claim 55, wherein identifying the initial 2D cross-section also includes identifying adjacent ones of the 2D cross-sections in which the interproximal surface of the tooth is obscured by gum tissue in one of the adjacent cross-sections and is not obscured by gum tissue in the other adjacent cross-section.

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57. The method of claim 56, wherein identifying the initial 2D cross-section also includes selecting as the initial 2D cross-section the adjacent cross-section in which the interproximal surface of the tooth is not obscured by gum tissue.

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58. The method of claim 55, wherein identifying the initial 2D cross-section also includes, for

each of the isolated cross-sections, establishing a contour line that outlines the shape of the dentition in that cross-section.

59. The method of claim 58, wherein identifying the initial 2D cross-section also includes
5 applying a test to each of the isolated cross-sections to identify those cross-sections in which the interproximal surface of the tooth is not obscured by gum tissue.

60. The method of claim 59, wherein applying the test includes calculating the rate of curvature of the contour line.

10 61. The method of claim 59, wherein identifying the initial 2D cross-section includes selecting as the initial 2D cross-section the isolated cross-section that lies closest to the roots of the tooth and in which the interproximal surface of the tooth is not obscured by gum tissue.

15 62. The method of claim 30, wherein applying the computer-implemented test also includes identifying two elements of the data set that define endpoints of a line segment spanning the relative minimum width of the initial 2D cross-section.

63. The method of claim 62, wherein applying the computer-implemented test also includes defining, for each endpoint, a neighborhood containing a predetermined number of elements of the data set near the endpoint in the initial 2D cross-section.

5 64. The method of claim 63, wherein applying the computer-implemented test also includes identifying an additional 2D cross-section of the individual component in a plane parallel and adjacent to the initial 2D cross-section, where the additional 2D cross-section also has a continuous, latitudinal width with a relative minimum value occurring at one end of the cross-section.

10 65. The method of claim 64, wherein applying the computer-implemented test also includes

identifying two elements of the data set that define endpoints of a line segment spanning the relative minimum width of the additional 2D cross-section by:

- (a) defining two neighborhoods of data elements, each containing elements of the data set that are adjacent to the data elements contained in the neighborhoods defined for the initial 2D cross-section; and
- (b) identifying one data element in each neighborhood that corresponds to one of the endpoints of the line segment spanning the relative minimum width of the additional 2D cross-section.

66. The method of claim 65, further comprising establishing a solid surface that is fitted among line segments spanning the relative minimum widths of the parallel 2D cross-sections.

67. The method of claim 66, wherein the individual component to be modeled is a tooth and the solid surface represents an interproximal surface of the tooth.

68. The method of claim 30, further comprising receiving information provided by a human user that identifies elements of the data set that correspond to the relative minimum width of the initial 2D cross-section.

69. The method of claim 68, further comprising displaying a graphical representation of the patient's dentition in which the user identifies portions corresponding to the relative minimum width of the cross-section.

70. The method of claim 69, wherein the graphical representation is three dimensional.

71. The method of claim 69, wherein the graphical representation includes a 2D representation of the initial 2D cross-section.

72. The method of claim 71, further comprising receiving the information from an input device

used by the human user to identify the relative minimum width of the initial 2D cross-section in the graphical representation.

73. The method of claim 71, wherein the initial 2D cross-section is one of many 2D cross-sections displayed to the human user.

74. The method of claim 71, further comprising receiving information from the human user identifying which of the displayed 2D cross-sections is the initial 2D cross-section.

75. A computer-implemented method for use in creating a digital model of a tooth in a patient's dentition, the method comprising:

- (a) receiving a three-dimensional (3D) data set representing the patient's dentition;
- (b) applying a computer-implemented test to identify data elements that represent an interproximal margin between two teeth in the dentition;
- (c) applying another computer-implemented test to select data elements that lie on one side of the interproximal margin for inclusion in the digital model.

76. The method of claim 75, further comprising creating a set of 2D planes that intersect the dentition roughly perpendicular to an occlusal plane of the dentition, each 2D plane including data elements that form a 2D cross-section of the dentition.

77. The method of claim 76, further comprising identifying the 2D plane with the smallest cross-sectional area.

78. The method of claim 77, further comprising rotating the 2D plane with the smallest cross-sectional area to at least one other orientation to form at least one other 2D cross-section of the dentition.

79. The method of claim 78, further comprising selecting the orientation that gives the rotated

plane its smallest possible cross-sectional area.

80. The method of claim 79, further comprising identifying data elements that represent the selected orientation of the rotated plane as lying on an interproximal margin.

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81. The method of claim 78, wherein the plane is rotated about two orthogonal lines passing through its center point.

82. The method of claim 77, further comprising creating a set of additional 2D planes in the vicinity of the 2D plane with the smallest cross-sectional area.

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83. The method of claim 82, further comprising identifying the plane in the set of additional planes that has the smallest cross-sectional area.

84. The method of claim 83, further comprising rotating the plane with the smallest cross-sectional area to at least one other orientation to form at least one other 2D cross-section of the dentition.

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85. The method of claim 84, further comprising selecting the orientation that produces the 2D cross-section with the smallest possible area.

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86. The method of claim 76, wherein creating a set of 2D planes includes creating an initial plane near one end of the dentition.

87. The method of claim 86, further comprising selecting a point in the dentition that is a predetermined distance from the initial plane and creating a second plane.

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88. The method of claim 87, wherein the second plane is roughly parallel to the initial plane.

89. The method of claim 87, further comprising rotating the second plane to at least one additional orientation to form at least one additional 2D cross-section of the dentition.

90. The method of claim 89, further comprising selecting the orientation that produces the 2D cross-section with the smallest cross-sectional area.

91. The method of claim 89, further comprising selecting a point that is a predetermined distance from the second plane and creating a third plane that includes the selected point.

92. The method of claim 91, further comprising rotating the third plane to at least one other orientation to create at least one additional 2D cross-section of the dentition.

93. The method of claim 91, further comprising creating additional planes, each including a point that is a predetermined distance from a preceding plane, until the other end of the dentition is reached.

94. The method of claim 93, further comprising identifying at least one plane having a local minimum in cross-sectional area.

95. The method of claim 93, further comprising identifying a centerpoint of the cross-section in each of the planes and creating a curve that fits among the identified centerpoints.

96. The method of claim 95, further comprising creating a set of additional 2D planes along the curve, where the curve is roughly normal to each of the additional planes, and where each of the additional planes is roughly perpendicular to the occlusal plane.

97. The method of claim 96, further comprising identifying at least one of the additional planes that has a local minimum in cross-sectional area.

98. A computer-implemented method for use in creating a digital model of a tooth in a patient's dentition, the method comprising:

- (a) receiving a 3D dataset representing at least a portion of the patient's dentition, including at least a portion of a tooth and gum tissue surrounding the tooth;
- (b) applying a test to identify data elements lying on a gingival boundary that occurs where the tooth and the gum tissue meet; and
- (c) applying a test to the data elements lying on the boundary to identify other data elements representing portions of the tooth.

99. The method of claim 98, wherein applying the test to identify data elements on the gingival boundary includes creating an initial 2D plane that intersects the dentition roughly perpendicular to an occlusal plane of the dentition and that includes data elements representing an initial cross-sectional surface of the dentition.

100. The method of claim 99, wherein applying the test includes locating a cusp in the initial cross-sectional surface.

101. The method of claim 100, wherein locating the cusp includes calculating rate of curvature of the initial cross-sectional area at selected points on the cross-sectional surface.

102. The method of claim 101, wherein locating the cusp includes identifying the point at which the rate of curvature is greatest.

103. The method of claim 100, wherein applying the test includes creating a second 2D plane that is roughly parallel to the initial 2D plane and that includes data elements representing a second cross-sectional surface of the dentition.

104. The method of claim 103, wherein applying the test includes locating a cusp in the second cross-sectional surface.

105. The method of claim 104, wherein locating the cusp in the second cross-sectional surface includes defining a neighborhood of data elements around the cusp in the initial cross-sectional surface and projecting the neighborhood onto the second cross-sectional surface.

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106. The method of claim 105, wherein locating the cusp in the second cross-sectional surface includes searching for the cusp only within the neighborhood projected onto the second cross-sectional surface.

10 107. The method of claim 99, wherein applying the test includes locating two cusps in the initial cross-sectional surface.

108. The method of claim 107, wherein applying the test includes creating a second 2D plane that is roughly parallel to the initial 2D plane and that includes data elements representing a second cross-sectional surface of the dentition.

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109. The method of claim 108, wherein applying the test includes locating two cusps in the second cross-sectional surface.

20 110. The method of claim 109, wherein locating the cusps in the second cross-sectional surface includes defining two neighborhoods of data elements around the two cusps in the initial cross-sectional surface and projecting the neighborhoods onto the second cross-sectional surface.

25 111. The method of claim 110, wherein each neighborhood projected onto the second cross-sectional surface includes data elements representing portions of the tooth and data elements representing the gum tissue surrounding the tooth.

112. The method of claim 111, wherein the data elements representing the tooth include voxels

of one color and the data elements representing the gum tissue include voxels of another color.

113. The method of claim 111, wherein locating the cusps in the second cross-sectional surface includes locating the pair of data elements representing gum tissue that lie closest together, where each of the two neighborhoods projected onto the second cross-sectional surface includes one of the data elements in the pair.

114. The method of claim 98, wherein applying the test to identify data elements on the gingival boundary includes creating a series of roughly parallel 2D planes, each intersecting the dentition roughly perpendicular to an occlusal plane of the dentition, and each including data elements that represent a cross-sectional surface of the dentition.

115. The method of claim 114, wherein the cross-sectional surface in each 2D plane includes two cusps that roughly identify the locations of the gingival boundary.

116. The method of claim 115, wherein applying the test includes identifying the cusps in each cross-sectional surface.

117. The method of claim 116, wherein identifying the cusps includes locating the cusps in one of the planes and then confining the search for cusps in an adjacent plane to a predetermined area in the vicinity of the identified cusps.

118. The method of claim 115, further comprising allowing a human user to select data elements that roughly identify the locations of the cusps in a selected one of the cross-sectional areas.

119. The method of claim 118, further comprising searching for cusps in the selected cross-sectional area and confining the search to data elements lying within a predetermined area in the vicinity of the data elements selected by the human user.

120. The method of claim 118, further comprising searching for cusps in an adjacent cross-sectional area and confining the search to data elements lying within a predetermined area in the vicinity of the data elements selected by the human user.

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121. A computer program, stored on a tangible storage medium, for use in creating a digital model of an individual component of a patient's dentition, the program including executable instructions that, when executed by a computer, cause the computer to:

- (a) receive a data set that forms a three-dimensional (3D) representation of the patient's dentition;
- (b) apply a test to the data set to identify data elements that represent portions of an individual component of the patient's dentition; and
- (c) create a digital model of the individual component based upon the identified data elements.

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122. The program of claim 121, wherein the computer receives the data, applies the test, and creates the electronic model without human intervention.

123. The program of claim 121, wherein the computer, in applying the test, applies a rule to identify a boundary of the individual component to be modeled.

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124. The program of claim 121, wherein the computer, in applying the test, identifies elements of the data set that represent a structural core of the individual component to be modeled and labels those data elements as belonging to the individual component.

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125. The program of claim 124, wherein the computer, in applying the test, links other data elements to those representing the structural core and labels the linked data elements as belonging to the individual component.

126. The program of claim 125, wherein the computer, in applying the test:

- (a) assigns a distance measure to each element of the data set, where the distance measure indicates a measured distance between a reference point in the dentition and the portion of the dentition represented by the data element to which the distance measure is assigned; and
- (b) links a data element to the structural core if the assigned distance measure is less than the distance measure assigned to a data element representing a portion of the structural core.

127. The program of claim 121, wherein the computer, in applying the test, identifies an initial 2D cross-section of the individual component having continuous latitudinal width, a relative minimum value of which occurs at an end of the initial cross-section.

128. The program of claim 127, wherein the computer, in applying the test, identifies the end of the initial cross-section at which the relative minimum value of the latitudinal width occurs by:

- (a) establishing line segments within the initial cross-section, each of which is bounded at each end by an endpoint lying on a surface of the individual component, and each of which is roughly perpendicular to a latitudinal axis of the individual component;
- (b) calculating a length for each line segment; and
- (c) identifying elements of the data set that correspond to the endpoints of the line segment with the shortest length.

129. The program of claim 128, wherein the computer, in applying the test:

- (a) isolates portions of the data set corresponding to other 2D cross-sections of the individual component, all lying in planes parallel to the initial 2D cross-section;
- (b) for each of the other cross-sections, identifies data elements that correspond to endpoints of a line segment representing an end of the cross-section; and
- (c) defines a solid surface that contains all of the identified data elements.

130. The program of claim 128, wherein the computer, in applying the test:

- (a) first creates an initial curve that is roughly perpendicular to the latitudinal axis of the individual component and that is fitted between the surfaces of the 2D cross-section on which the endpoints of the line segments lie;
- (b) establishes a set of initial line segments that are roughly perpendicular to the curve and to the latitudinal axis and that have endpoints lying on the surfaces of the individual component;
- (c) pivots each initial line segment about a point at which the initial line segment intersects the curve until the initial line segment has its shortest possible length;
- (d) locates a midpoint for each of the initial line segments after pivoting; and
- (e) creates a refined curve that passes through all of the midpoints and that is roughly normal to all of the line segments.

131. The program of claim 128, wherein the computer, in applying the test, also:

- (a) establishes an initial line segment by creating a line that intersects the initial 2D cross-section, such that the initial line segment is bounded by endpoints that lie on surfaces of the individual component;
- (b) establishes at least one additional line segment parallel to and spaced a predetermined distance from a previously established line segment; and
- (c) for each additional line segment, locates a midpoint of the additional line segment and pivots the additional line segment about the midpoint until the additional line segment has its shortest possible length.

132. The program of claim 131, wherein the computer, in applying the test, also:

- (a) establishes a curve that is fitted among the midpoints of the additional line segments;
- (b) establishes a new set of line segments that are perpendicular to the curve;
- (c) locates midpoints for each of the line segments in the new set; and
- (d) pivots each line segment in the new set about its midpoint until the line segment has its shortest possible length.

133. The program of claim 127, wherein the individual component is a tooth and the relative minimum value of the initial 2D cross-section lies on an interproximal surface of the tooth.

134. The program of claim 133, wherein the computer, in identifying the initial 2D cross-section, isolates elements of the data set that correspond to 2D cross-sections of the tooth lying in parallel planes between the roots and the occlusal surface of the tooth.

135. The program of claim 134, wherein the computer, in identifying the initial 2D cross-section, identifies adjacent ones of the 2D cross-sections in which the interproximal surface of the tooth is obscured by gum tissue in one of the adjacent cross-sections and is not obscured by gum tissue in the other adjacent cross-section.

136. The program of claim 135, wherein the computer, in identifying the initial 2D cross-section, selects as the initial 2D cross-section the adjacent cross-section in which the interproximal surface of the tooth is not obscured by gum tissue.

137. The program of claim 134, wherein the computer, in identifying the initial 2D cross-section, identifies for each of the isolated cross-sections a contour line that outlines the shape of the dentition in that cross-section.

138. The program of claim 137, wherein the computer, in identifying the initial 2D cross-section, applies a test to each of the isolated cross-sections to identify those cross-sections in which the interproximal surface of the tooth is not obscured by gum tissue.

139. The program of claim 138, wherein the computer, in applying the test to each of the isolated cross-sections, calculates the rate of curvature of the contour line.

140. The program of claim 138, wherein the computer, in identifying the initial 2D cross-section, selects as the initial 2D cross-section the isolated cross-section that lies closest to

the roots of the tooth and in which the interproximal surface of the tooth is not obscured by gum tissue.

- 5 141. The program of claim 127, wherein the computer, in applying the test, identifies two elements of the data set that define endpoints of a line segment spanning the relative minimum width of the initial 2D cross-section.
142. The program of claim 141, wherein the computer, in applying the test, defines for each endpoint a neighborhood containing a predetermined number of elements of the data set near the endpoint in the initial 2D cross-section.
- 5 143. The program of claim 142, wherein the computer, in applying the test, identifies an additional 2D cross-section of the individual component in a plane parallel and adjacent to the initial 2D cross-section, where the additional 2D cross-section also has a continuous, latitudinal width with a relative minimum value occurring at one end of the cross-section.
- 10 144. The program of claim 143, wherein the computer, in applying the test, identifies two elements of the data set that define endpoints of a line segment spanning the relative minimum width of the additional 2D cross-section by:
- 15 (a) defining two neighborhoods of data elements, each containing elements of the data set that are adjacent to the data elements contained in the neighborhoods defined for the initial 2D cross-section; and
- (b) identifying one data element in each neighborhood that corresponds to one of the endpoints of the line segment spanning the relative minimum width of the additional 2D cross-section.
- 20 145. The program of claim 144, wherein the computer also establishes a solid surface that is fitted among line segments spanning the relative minimum widths of the parallel 2D cross-sections.

146. The program of claim 145, wherein the individual component to be modeled is a tooth and the solid surface represents an interproximal surface of the tooth.

147. A computer program, stored on a tangible storage medium, for use in creating a digital model of tooth in a patient's dentition, the program including executable instructions that, when executed by a computer, cause the computer to:

- (a) receive a three-dimensional (3D) data set representing the patient's dentition;
- (b) apply a test to identify data elements that represent an interproximal margin between two teeth in the dentition;
- (c) apply another test to select data elements that lie on one side of the interproximal margin for inclusion in the digital model.

148. The program of claim 147, wherein the computer creates a set of 2D planes that intersect the dentition roughly perpendicular to an occlusal plane of the dentition, each 2D plane including data elements that form a 2D cross-section of the dentition.

149. The program of claim 148, wherein the computer identifies the 2D plane with the smallest cross-sectional area.

150. The program of claim 149, wherein the computer rotates the 2D plane with the smallest cross-sectional area to at least one other orientation to form at least one other 2D cross-section of the dentition.

151. The program of claim 150, wherein the computer selects the orientation that gives the rotated plane its smallest possible cross-sectional area.

152. The program of claim 151, wherein the computer identifies data elements that represent the selected orientation of the rotated plane as lying on an interproximal margin.

153. The program of claim 150, wherein the computer rotates the plane about two orthogonal lines passing through its center point.

5 154. The program of claim 149, wherein the computer creates a set of additional 2D planes in the vicinity of the 2D plane with the smallest cross-sectional area.

155. The program of claim 154, wherein the computer identifies the plane in the set of additional planes that has the smallest cross-sectional area.

10 156. The program of claim 155, wherein the computer rotates the plane with the smallest cross-sectional area to at least one other orientation to form at least one other 2D cross-section of the dentition.

15 157. The program of claim 156, wherein the computer selects the orientation that produces the 2D cross-section with the smallest possible area.

158. The program of claim 148, wherein the computer, in creating the set of 2D planes, creates an initial plane near one end of the dentition.

20 159. The program of claim 158, wherein the computer selects a point in the dentition that is a predetermined distance from the initial plane and creates a second plane that includes the selected point.

25 160. The program of claim 159, wherein the second plane is roughly parallel to the initial plane.

161. The program of claim 159, wherein the computer rotates the second plane to at least one additional orientation to form at least one additional 2D cross-section of the dentition.

162. The program of claim 161, wherein the computer selects the orientation that produces the 2D cross-section with the smallest cross-sectional area.

163. The program of claim 161, wherein the computer selects a point that is a predetermined distance from the second plane and creates a third plane that includes the selected point.

164. The program of claim 163, wherein the computer rotates the third plane to at least one other orientation to create at least one additional 2D cross-section of the dentition.

165. The program of claim 163, wherein the computer creates additional planes, each including a point that is a predetermined distance from a preceding plane, until the other end of the dentition is reached.

166. The program of claim 165, wherein the computer identifies at least one plane having a local minimum in cross-sectional area.

167. The program of claim 165, wherein the computer identifies a centerpoint of the cross-section in each of the planes and creates a curve that fits among the identified centerpoints.

168. The program of claim 167, wherein the computer creates a set of additional 2D planes along the curve, where the curve is roughly normal to each of the additional planes, and where each of the additional planes is roughly perpendicular to the occlusal plane.

169. The program of claim 168, wherein the computer identifies at least one of the additional planes that has a local minimum in cross-sectional area.

170. A computer program, stored on a tangible storage medium, for use in creating a digital model of a tooth in a patient's dentition, the program including executable instructions that, when executed by a computer, cause the computer to:

- (a) receive a 3D data set representing at least a portion of the patient's dentition, including at least a portion of a tooth and gum tissue surrounding the tooth;
- (b) apply a test to identify data elements lying on a gingival boundary that occurs where the tooth and the gum tissue meet; and
- (c) apply a test to the data elements lying on the boundary to identify other data elements representing portions of the tooth.

171. The program of claim 170, wherein the computer, in applying the test to identify data elements on the gingival boundary, creates an initial 2D plane that intersects the dentition roughly perpendicular to an occlusal plane of the dentition and that includes data elements representing an initial cross-sectional surface of the dentition.

172. The program of claim 171, wherein the computer locates a cusp in the initial cross-sectional surface.

173. The program of claim 172, wherein the computer, in locating the cusp, calculates rate of curvature of the initial cross-sectional area at selected points on the cross-sectional surface.

174. The program of claim 173, wherein the computer, in locating the cusp, identifies the point at which the rate of curvature is greatest.

175. The program of claim 172, wherein the computer creates a second 2D plane that is roughly parallel to the initial 2D plane and that includes data elements representing a second cross-sectional surface of the dentition.

176. The program of claim 175, wherein the computer locates a cusp in the second cross-

sectional surface.

177. The program of claim 176, wherein the computer, in locating the cusp in the second cross-sectional surface, defines a neighborhood of data elements around the cusp in the initial cross-sectional surface and projects the neighborhood onto the second cross-sectional surface.

178. The program of claim 177, wherein the computer, in locating the cusp in the second cross-sectional surface, searches for the cusp only within the neighborhood projected onto the second cross-sectional surface.

179. The program of claim 171, wherein the computer locates two cusps in the initial cross-sectional surface.

180. The program of claim 179, wherein the computer creates a second 2D plane that is roughly parallel to the initial 2D plane and that includes data elements representing a second cross-sectional surface of the dentition.

181. The program of claim 180, wherein the computer locates two cusps in the second cross-sectional surface.

182. The program of claim 181, wherein the computer, in locating the cusps in the second cross-sectional surface, defines two neighborhoods of data elements around the two cusps in the initial cross-sectional surface and projects the neighborhoods onto the second cross-sectional surface.

183. The program of claim 182, wherein each neighborhood projected onto the second cross-sectional surface includes data elements representing portions of the tooth and data elements representing the gum tissue surrounding the tooth.

184. The program of claim 183, wherein the data elements representing the tooth include voxels of one color and the data elements representing the gum tissue include voxels of another color.

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185. The program of claim 183, wherein the computer, in locating the cusps in the second cross-sectional surface, locates the pair of data elements representing gum tissue that lie closest together, where each of the two neighborhoods projected onto the second cross-sectional surface includes one of the data elements in the pair.

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186. The program of claim 170, wherein the computer, in applying the test to identify data elements on the gingival boundary, creates a series of roughly parallel 2D planes, each intersecting the dentition roughly perpendicular to an occlusal plane of the dentition, and each including data elements that represent a cross-sectional surface of the dentition.

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187. The program of claim 186, wherein the cross-sectional surface in each 2D plane includes two cusps that roughly identify the locations of the gingival boundary.

188. The program of claim 187, wherein the computer identifies the cusps in each cross-sectional surface.

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189. The program of claim 188, wherein the computer, in identifying the cusps, locates the cusps in one of the planes and then confines the search for cusps in an adjacent plane to a predetermined area in the vicinity of the identified cusps.

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190. The program of claim 187, wherein the computer allows a human user to select data elements that roughly identify the locations of the cusps in a selected one of the cross-sectional areas.

191. The program of claim 188, wherein the computer searches for cusps in the selected cross-sectional area and confines the search to data elements lying within a predetermined area in the vicinity of the data elements selected by the human user.

- 5 192. The program of claim 188, wherein the computer searches for cusps in an adjacent cross-sectional area and confines the search to data elements lying within a predetermined area in the vicinity of the data elements selected by the human user.

ABSTRACT

A computer or other digital circuitry is used to assist in the creation of a digital model of an individual component, such as a tooth or gum tissue, in a patient's dentition. The computer receives a data set that forms a three-dimensional (3D) representation of the patient's dentition, applies a test to the data set to identify data elements that represent portions of the individual component, and creates a digital model of the individual component based upon the identified data elements. Many implementations require the computer to identify data elements representing a 2D cross-section of the dentition lying in a 2D plane that is roughly parallel to or roughly perpendicular to the dentition's occlusal plane. The computer analyzes the 2D cross-section to identify dentition features that represent boundaries between individual dentition components.

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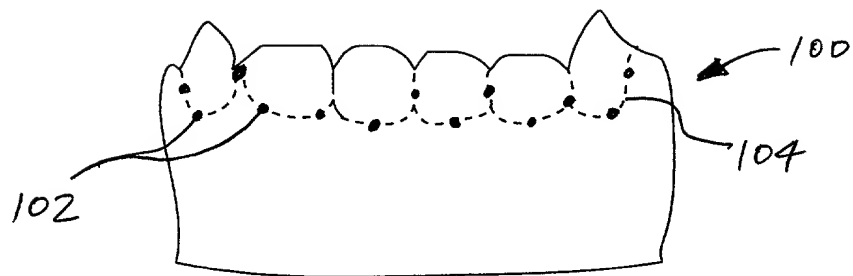


FIG. 1A

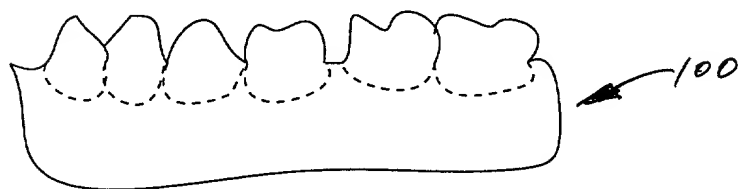


FIG. 1B

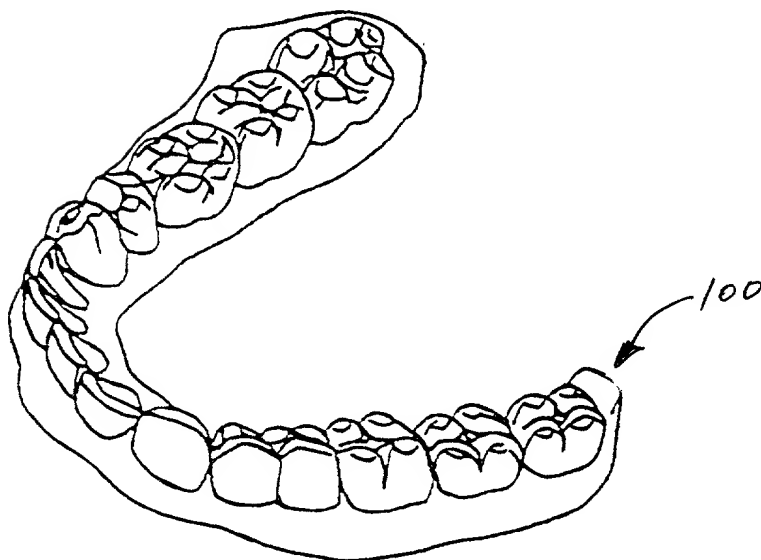


FIG. 2

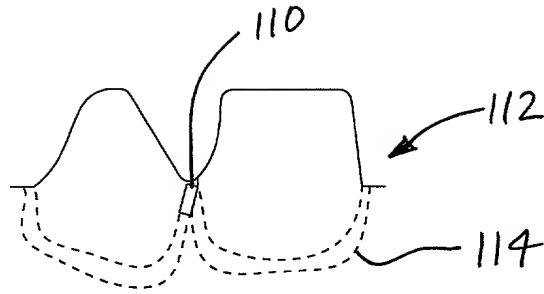


FIG. 3

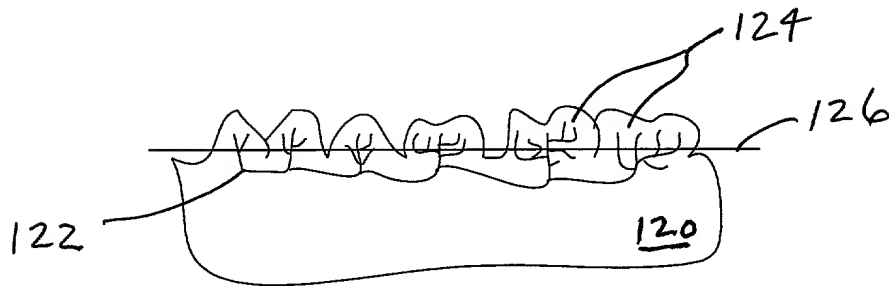


FIG. 4

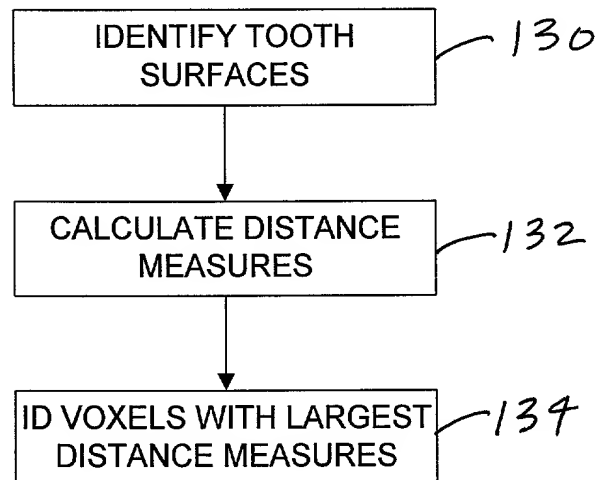


FIG. 5

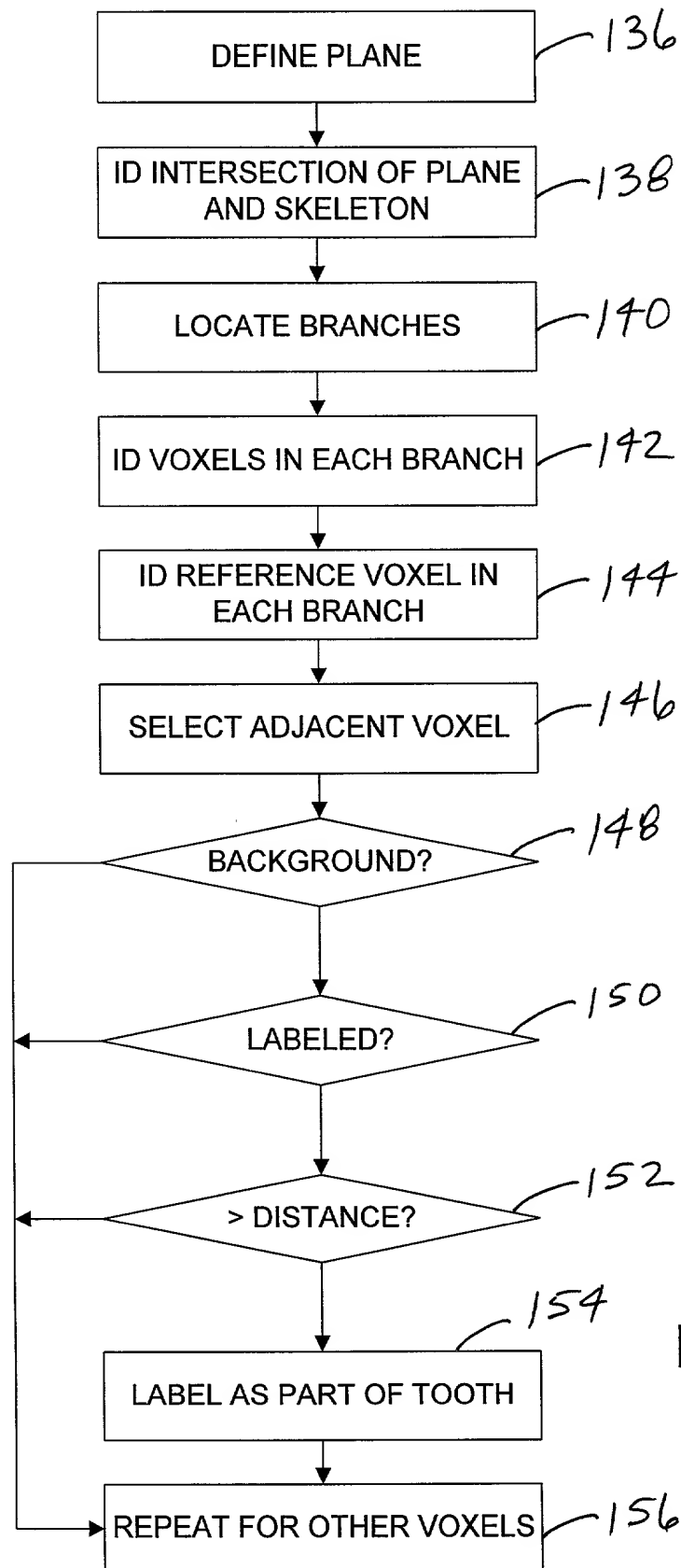


FIG. 6

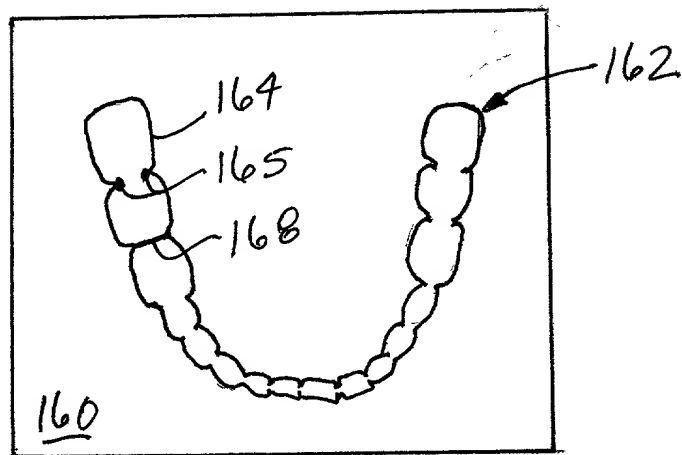


FIG. 7A

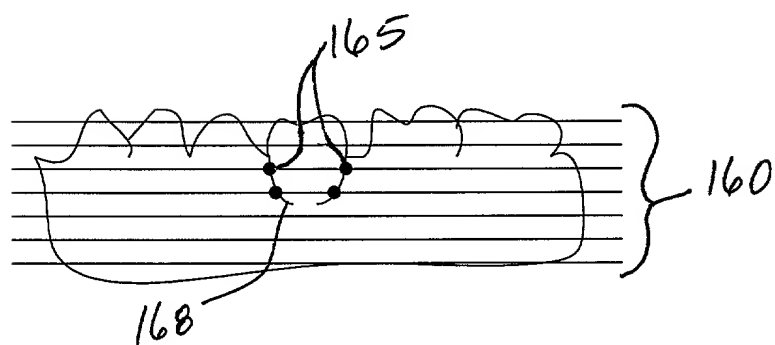


FIG. 7B

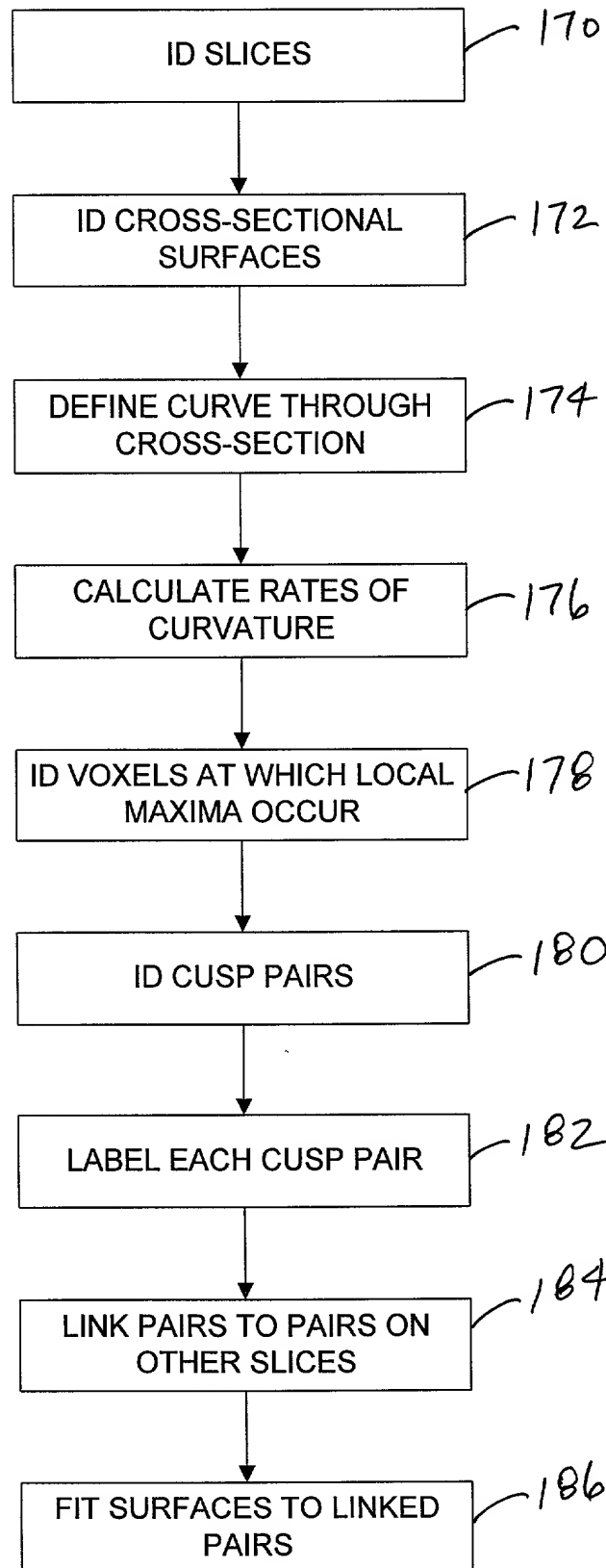


FIG. 8

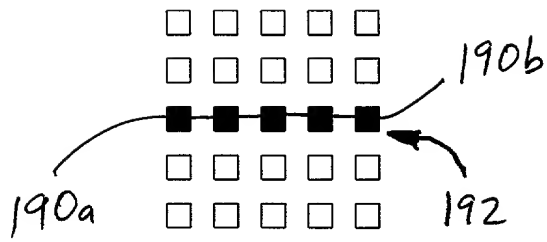


FIG. 9

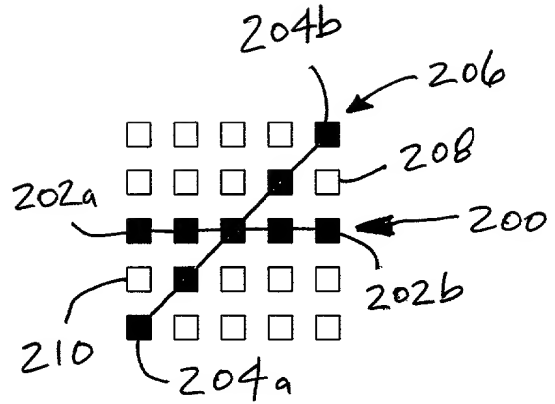


FIG. 10A

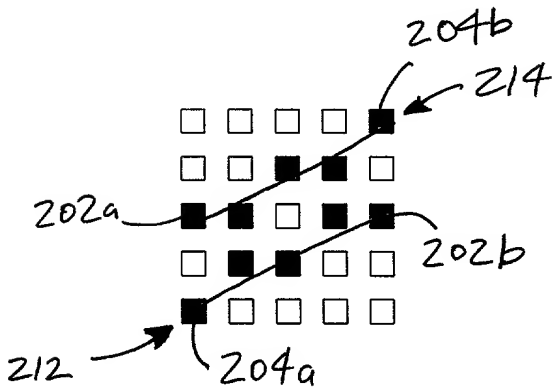


FIG. 10B

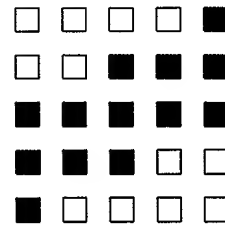


FIG. 10C

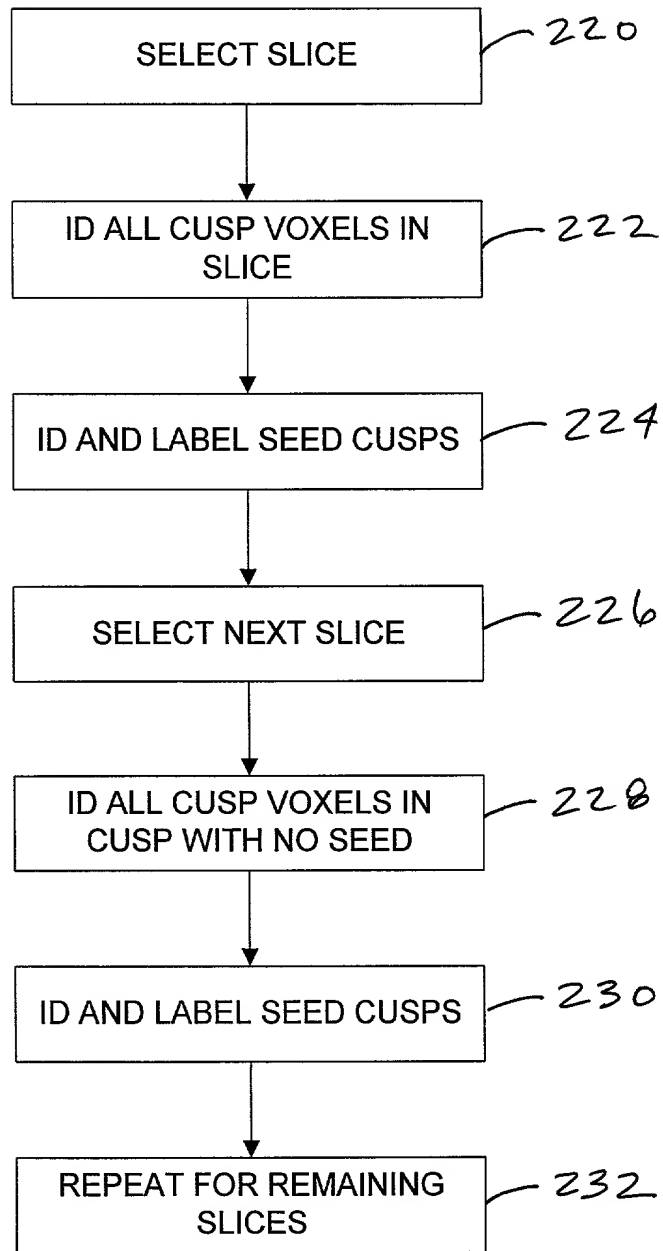


FIG. 11

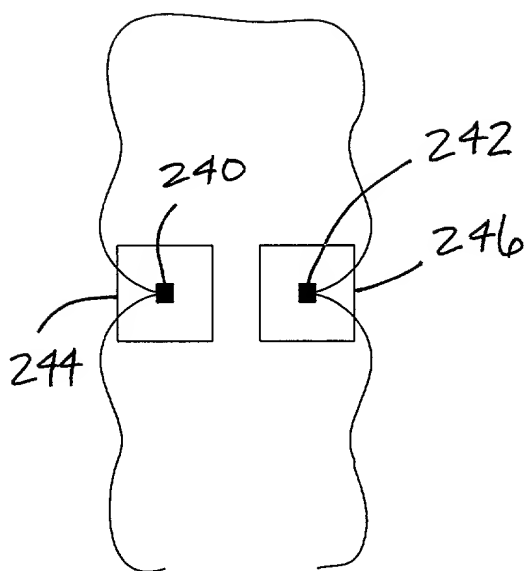


FIG. 12

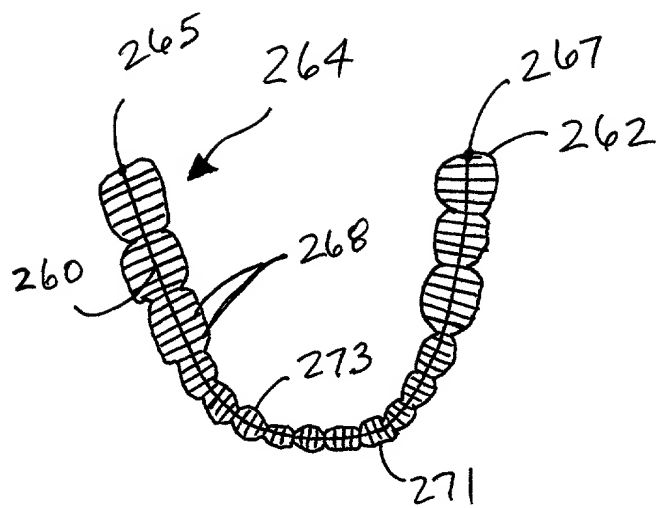


FIG. 15

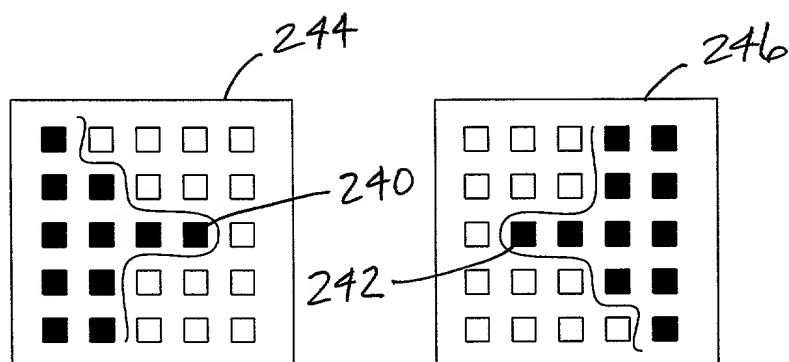


FIG. 13

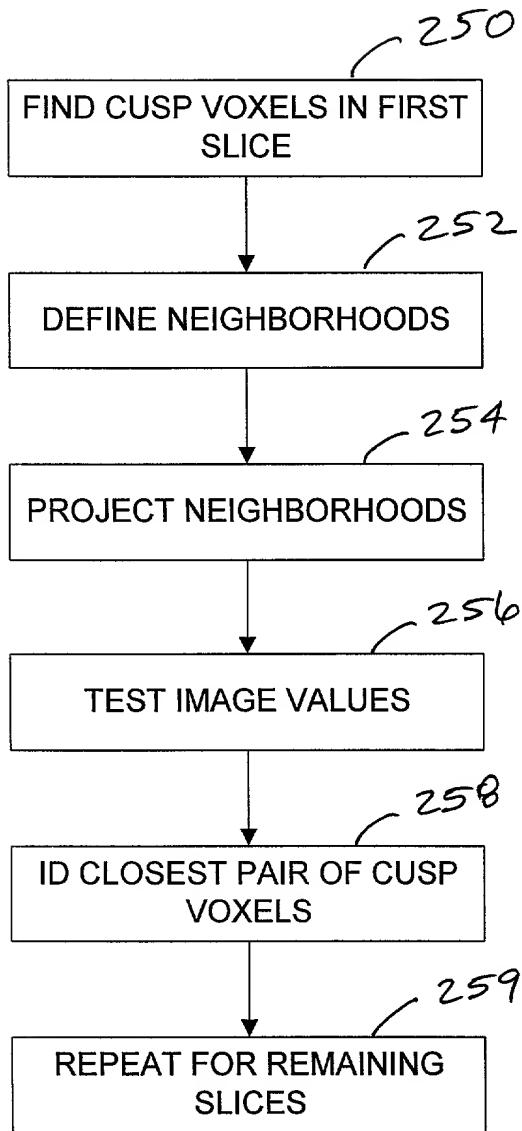


FIG. 14

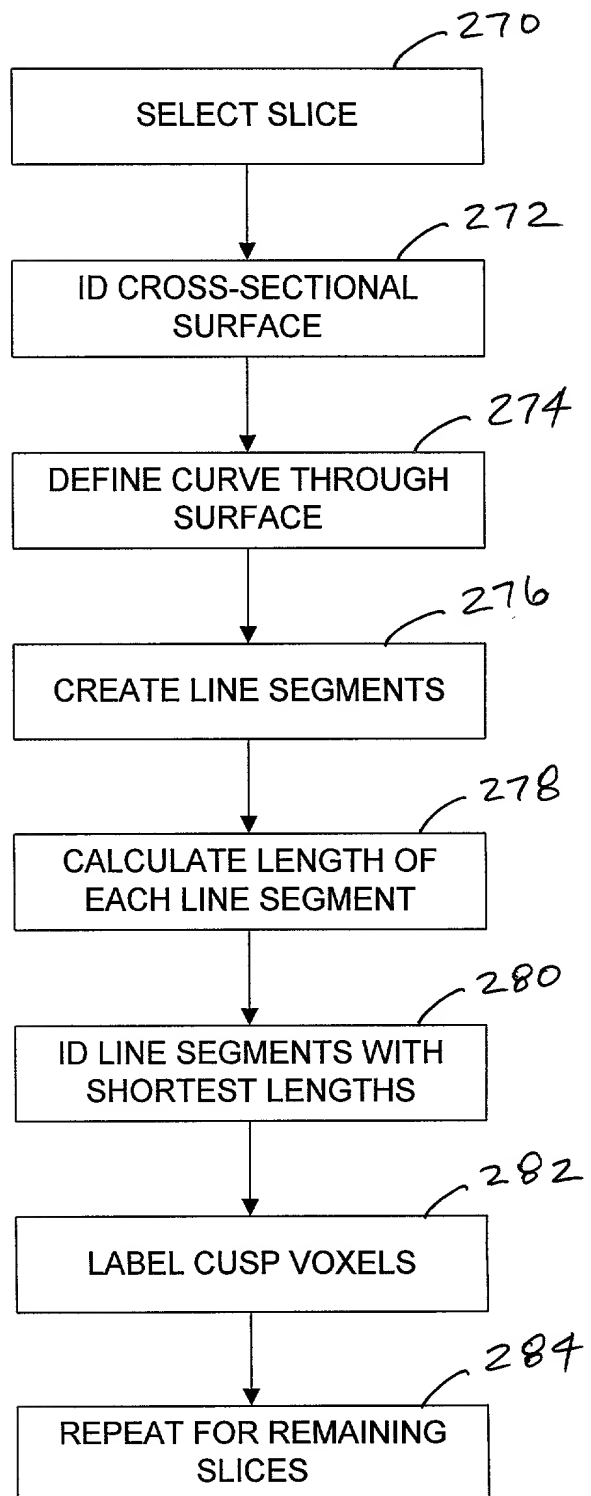


FIG. 16

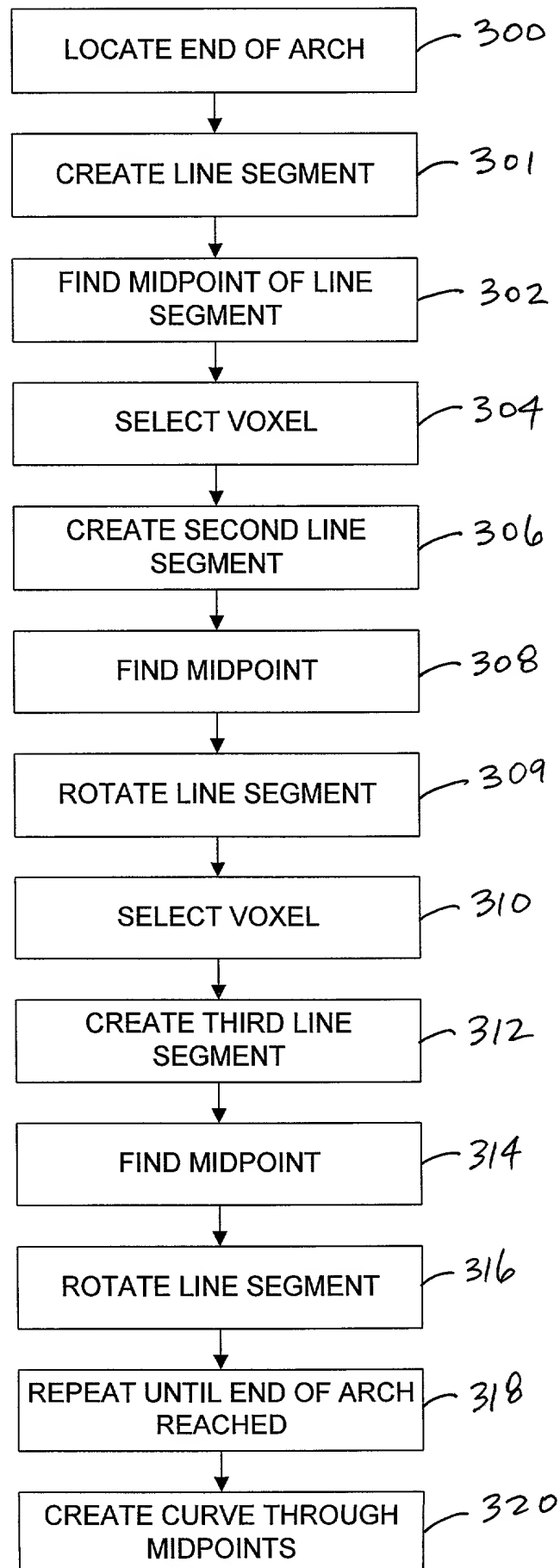


FIG. 18

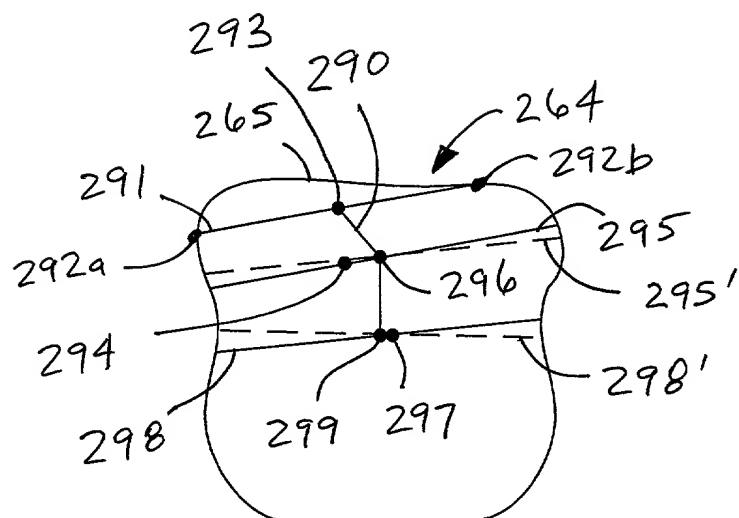


FIG. 17

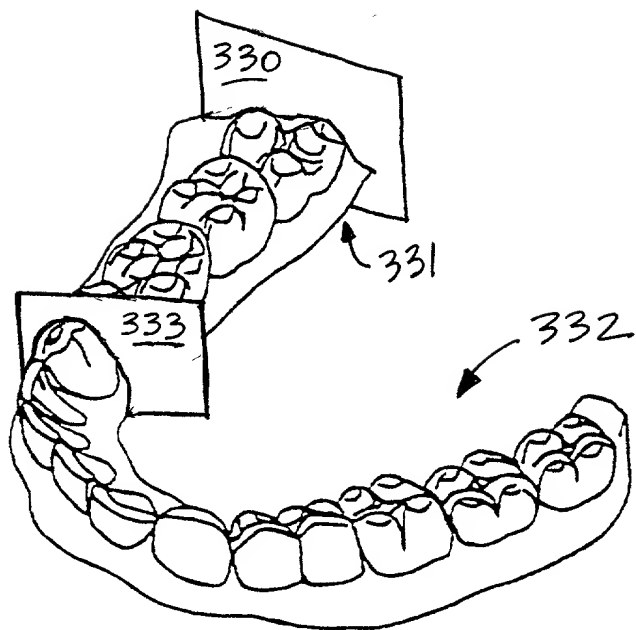


FIG. 19A

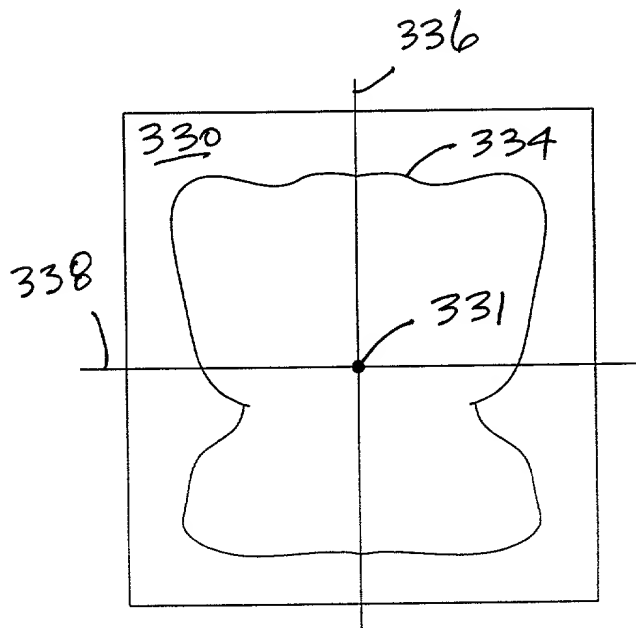


FIG. 19B

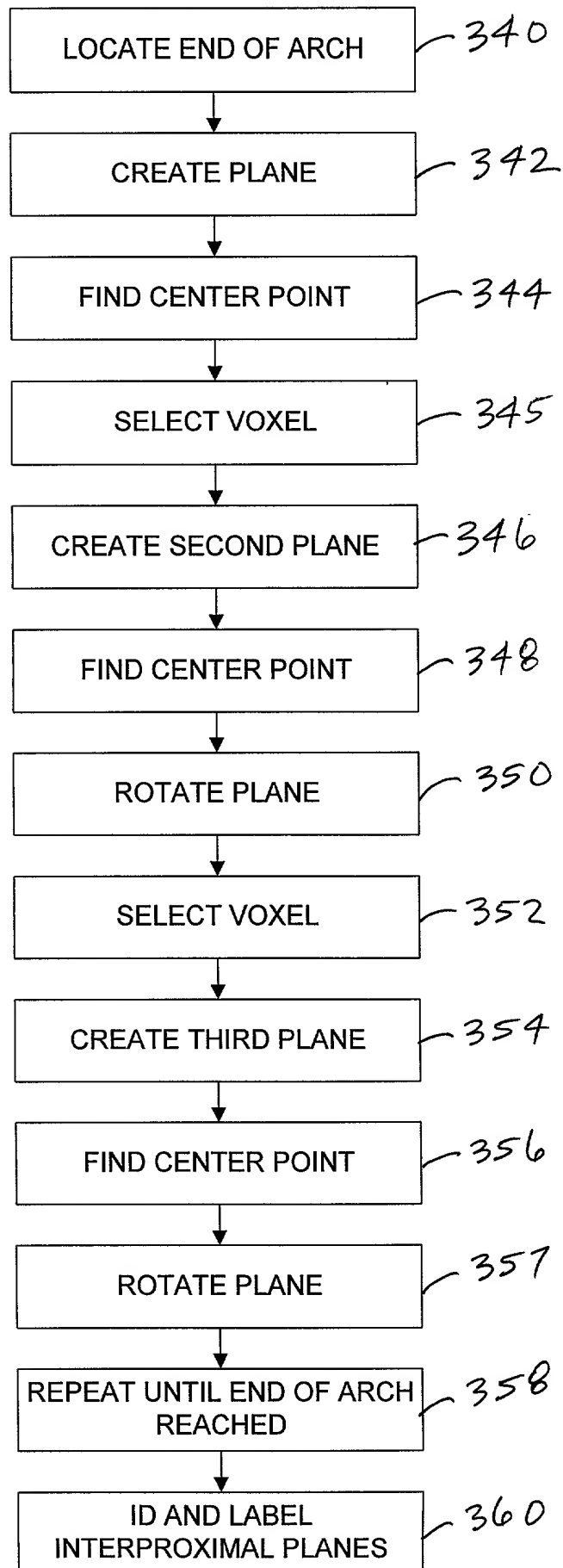


FIG. 20

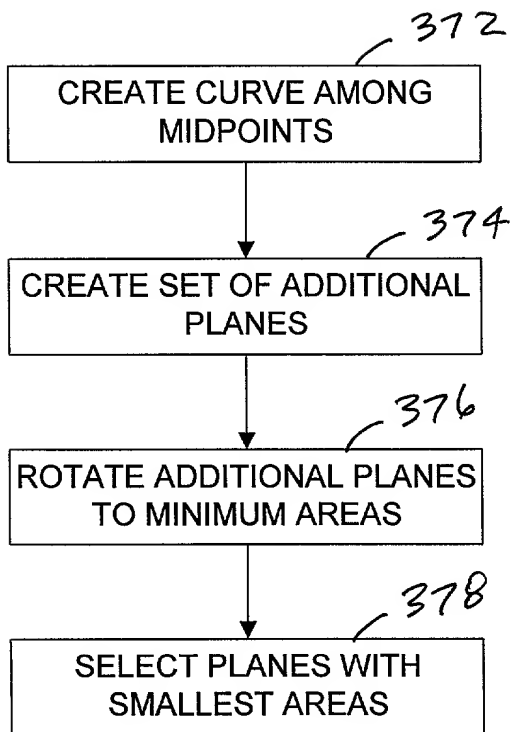


FIG. 21

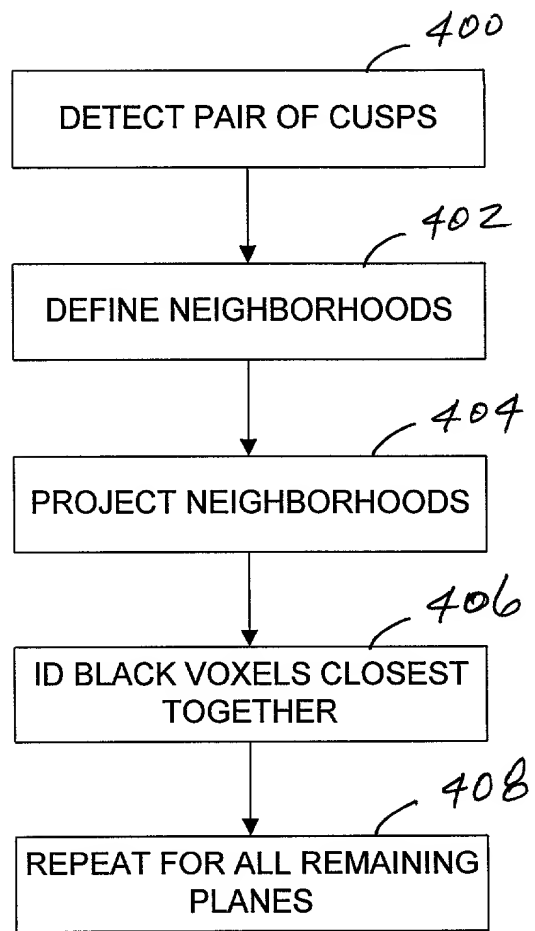


FIG. 24

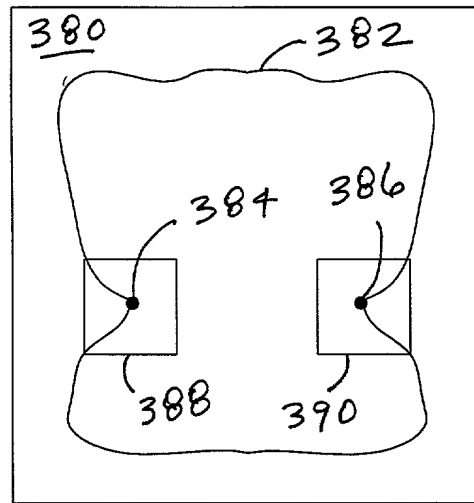


FIG. 22

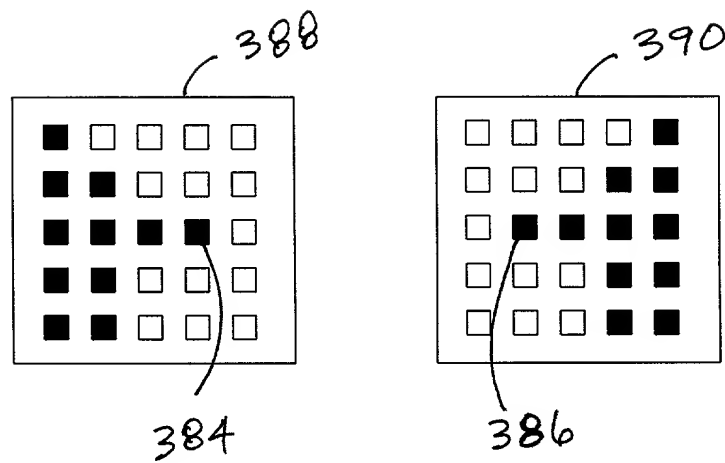


FIG. 23